Journal of Scientific & Industrial Research
Vol. 79, August 2020, pp. 686-690

Metakaolin Geopolymer Bricks and Prismsin Axial Compression

A R R Kalaiyarrasi[1]* and P Partheeban[2]

[1]St.Peter's Institute of Higher Education and Research, Chennai, Tamil Nadu, India
[2]Chennai Institute of Technology, Chennai, Tamil Nadu, India

Received 5 February 2018; revised 16 May 2019; accepted 29 April 2020

Metakaolin geopolymer bricks (MKGB) were synthesised in this investigation with different percentages of flyash (FA) and Metakaolin (MK). A desired strength of 5.5 N/mm^{2}is achieved by using 50% FA and 50% MK. The bricks were tested for properties like water absorption, initial rate of absorption, efflorescence, modulus of elasticity (MOE) and modular ratio. Initial rate of absorption for the MKGB is 0.5 Kg/m^2/min and the water absorption for MKGB is 3–5%. The Poisson's ratio (μ) for MKGB is 0.2 and E is 2340 MPa. Metakaolin Geopolymer brick prisms (MKBP) with aspect ratios ranging between 2–5 were constructed with 1:3 cement mortar. The compressive strength and the efficiency increases with the increase in aspect ratio of the masonry. The failure pattern is splitting and crushing of bricks rather than loss of bond between mortar and MKGB.

Keywords: Compressive Strength, MOE, Poisson's ratio

Introduction

Flyash bricks (FAB) are rapidly replacing clay bricks (CB) in the construction sector. FAB requires addition of cement or high-pressure casting or firing at high temperature or curing. Geopolymer[1,2] comprises of alumina-silicate rich source material and an alkali activator solution. No cement is used in geopolymers and it reduces the CO_2 emission by 80 % compared to cement-based materials. Geopolymers are durable and being inorganic, exhibit better fire resistance compared to cement-based materials.[3] Flyash is a widely used precursor in geopolymer synthesis. The smaller size (2 μm) and higher surface area (20 m^2/g) of MK particles compared to FA particles and the early setting of MK precursor[4] are taken advantage of in this experimental program to produce bricks of size 19 cm × 9 cm × 9 cm with a minimum compressive strength of 5.5 N/mm^2.

Materials and Methods

Materials

Flyash is a by-product of combustion of coal, fired in thermal power stations. In this investigation, low calcium (class F) FA which satisfies IS 3812[(5)] procured from Ennore thermal power station located in Chennai, Tamil Nadu, India was used. Physical property and chemical composition of FA and MK is given in Table 1. Meta in Metakaolin indicates the transformation of Kaolinite mineral through loss of hydroxyl ions. This process is known as hydroxylation or calcination. Calcining Kaolinite at the temperature range of 700ºC–800ºC for 4 hours and grinding to have a specific surface area of 20 m^2/g makes the clay highly reactive.[6] The particle shape of FA is spherical and MK is plate like.[7] Metakaolin is sourced from the mines of Gujarat and procured from Astra chemicals, Chennai.

Fine aggregate used in this investigation was natural sand conforming IS 2116[8], with a fineness modulus of 2.73. The two constituents of alkaline activator are NaOH and Na_2SiO_3 solutions. In one litre of distilled water 480 grams of 99% pure NaOH flakes were dissolved to prepare 12M NaOH. Distilled water is

Table 1 — Physical and Chemical properties of FA and MK

Chemical (% mass)	Metakaolin	Flyash
SiO_2	52.0	48.0
Al_2O_3	46.0	29.0
Fe_2O_3	0.60	12.7
TiO_2	0.65	—
CaO	0.09	1.76
MgO	0.03	0.89
Na_2O	0.10	0.39
K_2O	0.03	0.55
SO_3	—	0.5
Loss on ignition	1.00	1.61
Physical property		
Specific gravity	2.6	2.06
Specific surface area m^2/g	19–20	10.5

*Author for Correspondence
E-mail: ammu205@gmail.com

preferred to avoid impurities in dissolution. The solution of Na_2SiO_3 is viscid and translucent with pale white or grey colour. Sodium Silicate solution conforming to IS 381[9] Indian Standard sodium silicate –Specification is used in this investigation having Na_2O (8.74 %), SiO_2 (27.96%), H_2O (63.3%) with the modulus of 3.2 (mass of Na_2O/SiO_2=3.2).

Mix Design

The minimum compressive strength required for the bricks to be used for the structural purpose is 5.5 N/mm^2 according to IS 1905.[10] Two mix ratios of 1:5 and 1:6 of MK + FA and sand were identified for MKGB from the previous work of this authors[5] and in each mix ratio, the percentage of MK was varied from 0–75, and the remaining FA was used. Total (100%) replacement of metakaolin is not attempted as it may lead to shrinkage cracks and it is wise to use flyash. The solid-liquid ratio was maintained at 1. The ratio of NaOH solution and Na_2SiO_3 is maintained as 1:1.5. Eight different types of bricks of mix MK0, MK25, MK50, MK75 with 1:5 and 1:6 ratio of alumina-silicate precursor (FA+MK) and sand were cast and tested. Ten bricks of size 190 mm × 90 mm × 90 mm for each mix were cast and left in ambient condition for curing. Forty trial bricks were hand moulded using steel moulds.

Bricks of MK50 with 1:6 mix ratio provided the required compressive strength of 5.5 N/mm^2. One thousand bricks of MK50 mix were cast for use in the masonry. Cement mortar of 1:3 ratio was used for the construction of MKBP to replicate the Indian construction practice of using mortar stiffer than brick. Mortar Cubes of size 50 mm were cast with water cement ratio of 0.45 in accordance to IS 2250.[11] Cylinders of 150 mm diameter and 300 mm height were cast with the mortar used and tested for Young's modulus using compressometer.

Testing

The properties of bricks were tested in accordance with IS 3495.[12] The compressive strength of 20 number of MKGB at 21 days was tested in compression testing machine of 400 kN capacity with a rate of loading of 14 N/mm^2. Load at failure was taken as the ultimate compressive load. Percentage of water absorption was calculated after immersing the bricks in water for 24 hours. Efflorescence was calculated by immersing metakaolin geopolymer bricks on their ends in a square tray of 18 cm and depth of 60 cm. It was ensured that the minimum depth of immersion was 25 cm. The entire setup was closed with a lid to prevent evaporation of water to the atmosphere. When water is completely absorbed, a similar quantity of water is placed in the tray for evaporation. Bricks were examined for efflorescence after second evaporation.

Poisson's ratio (μ) is calculated using a quasi-static method of testing of bricks in compression. Three brick specimen in a vertical direction is tested in UTM of 1000 kN capacity. Dial gauges of Baker make with least count of 0.01mm and maximum of 25 mm are fixed in three directions and for every increment of load dial gauge reading is noted. Thin glass pieces are inserted at places of contact of the dial gauge and brick. As bricks in masonry are subjected to uniaxial stress or biaxial plane stress, the deformations in lengthwise (190 mm) and width-wise (90 mm) are considered for calculating Poisson's ratio. Lateral and longitudinal deformations are noted till 1/3 of the failure load. The tangent modulus is calculated between 5–33% of the ultimate stress. Average value is taken as MOE of the MKGB. Tangent modulus is slope of the stress strain diagram at any point.

Dynamic modulus of elasticity of MKGB was calculated by performing ultrasonic pulse velocity test. Portable ultrasonic non-destructive digital indicating tester unit of model Telsonicultrasonix UX 4600 pulse velocity was used with a transducer of 60 kHz of natural frequency. In this investigation, the direct transmission method was followed to assess the Dynamic Young's modulus of bricks. The test was conducted in accordance with IS 13311.[13] Time taken to travel the path length was digitally displayed. Velocity of the pulse was calculated using V = L/T where, V = Velocity of the pulse in m/s, L = Length of the path travelled in m, and T = Time taken in seconds

Taking μ from quasi-static method, dynamic modulus of elasticity is calculated using

$$E = \frac{\rho(1+\mu)(1-2\mu)V}{(1-\mu)} \quad \dots (1)$$

Where E, is Dynamic Young's Modulus of elasticity in MPa; ρ, density in kg/m^3; and V, pulse velocity in m/s

The properties of MKGB are tabulated in Table 2.

The critical properties of mortar are Poisson's ratio and modulus of Elasticity and not the compressive strength.[14] Three cylinders of 150 mm diameter and

300 mm height were cast with 1:3 cement mortar and tested for Young's modulus using compressometer. The compressometer is fitted with a dial gauge of 25 mm as largest deformation and a least count of 0.01 mm. Mortar cylinders were loaded up to 1/3 of the ultimate load and deformations were noted for equal increments of the load. Secant modulus of elasticity of the mortar was calculated using a slope at 25 percentage of ultimate strength in stress-strain graph in accordance with ACI 530-02.[15] Secant modulus is stress-strain ratio for given value of stress or strain. MOE of 1:3 cement mortar is 2.65 GPa. The compressive strength of 50 mm mortar cubes was tested in compression testing machine after 28 days of water curing. The compressive strength of 1:3 cement mortar at 28 days was 10 N/mm^2.

The behaviour of metakaolin modified geopolymer bricks in combination with cement mortar requires investigation for practical application. Laboratory investigation of masonry prisms was done in accordance with IS 1905-1987 Indian Standard Brick works-code of practice. Prisms were constructed with a minimum height of 40 cm with a height to thickness ratio of at least 2 but not more than 5. Correction factors were applied for prisms with h/t between 2 and 5. In joints and beddings, 10 mm mortar thickness was maintained. Testing of brick masonry prisms was done by loading frame of 500 kN capacity and a hydraulic jack of 250 kN. The hydraulic jack was fitted with a load cell of 250 kN capacity. Deformation in the masonry was measured using Linearly Varying Displacement Transducer (LVDT) with maximum deformation that could be measured as 10 cm.

Table 2 — Properties of MKGB

S. No	Property	MKGB
1	Size	190×90×90mm
2	Compressive strength	5.5 N/mm^2
3	Weight	2.9 kg
4	Efflorescence	nil
5	Initial Rate of absorption	0.5Kg/m^2/min
6	Water absorption	3–5%
7	Static E of brick	2340MPa
8	Dynamic E of brick	2490MPa
9	μ of brick	0.2

LVDT was attached to the prism by means of two L-shaped angles.[16] Angles were attached to the prisms by steel paste. The surface of the prism was smoothened by emery sheet to ensure perfect adhesion. Angles were pasted on to the prisms near the place where maximum deformation was expected. LVDT and load cell were connected to a data acquisition system which recorded the data in the computer connected to it.

MKBP were constructed with 1:3 C.M. with h/t ratio as given in Table 3.Three prisms for each h/t ratio was constructed and tested. Curing of MKBP with water was required for 28 days as cement mortar in the masonry needs curing. On the top of the prisms, 10 mm steel sheet was laid before testing for even distribution of load. Masonry was loaded till it displaces LVDT from its position and then LVDT was removed.

Results and Discussion

Permissible water absorption of flyash bricks is in the range of 15–20% as specified in IS 12894.[17] The compressive strength for geopolymer blocks with ground granulated blast furnace slag (GGBFS), Class F flyash and M-sand[18] varied from 17–28 N/mm^2 at 28 days and the water absorption was 8 % – 6.5 %. The compressive strength of the brick synthesised with MK-GGBFS[19] was 70 N/mm^2 and water absorption of 11–15.5% MKGB in this investigation have the water absorption range as 3–5% and almost nil efflorescence. MKGB needs no water curing or high temperature curing. In this investigation, MKBP are constructed with 1:3 cement mortar to have uniformity. The compressive strength of 1:3 cement mortar at 28 days is 10 N/mm^2. According to IS 2250, the 28 day compressive strength of 1:3 cement mortar should be above 7.5 N/mm^2. The MOE of 1:3 cement mortar is 2.65 GPa.

The MOE of cement mortar can be 400–100 times of compressive strength.[13] In this study, MOE of 1:3 cement mortar is 265 times of its compressive strength. Cement mortar used in this study is stronger and stiffer than MKGB which form a major part of

Table 3 — MOE and Compressive Strength of MKBP

Size in mm	h/t ratio	Bonding type	Ultimate Stress (MPa)		MOE (MPa)	Masonry efficiency
			This investigation	(Gumaste)		
490 × 90 × 190	5.44	Stretcher	1.8	1.86	912	0.32
490 × 190 × 190	2.57	English	1.5	2.15	847	0.27
590 × 190 × 600	3.1	English	1.8	2.15	1458	0.32
790 × 190 × 600	4.1	English	2.0	2.15	1824	0.36

masonry with thin layers of mortar providing the required adhesion between the bricks. Hence the efficiency of the masonry is adjudged by comparing the compressive strength of brick and masonry as

$$Masonry\ efficiency = \frac{Compressive\ \ strength\ of\ masonry}{Compressive\ \ strength\ of\ brick} \qquad \dots (2)$$

MKBP with h/t ratios of 5.44, 2.77, 3.1 and 4.15 were tested for axial compressive strength and MOE to understand the behaviour of MKGB in combination with cement mortar which is the type of mortar used in practice. As it is customary to test 5 bricks stacked one above the other (Stretcher bond) the h/t ratio exceeds 5 in the first prism. The prism with h/t ratio equal to 2.77 is also 5 brick height but in English bond. MKGB bonds well with the cement mortar and there is no failure of bond in the MKBP. The stress strain curve of the various MKBP is presented in Fig. 1. The ultimate stress values in English bond prisms reduce with the reduction in aspect ratio. Ultimate stress of stretcher bond prism with h/t ratio of 5.4 is 1.8 MPa compared to ultimate stress of 2.0 MPa for English bond prism with h/t ratio of 4.15. As it is customary to test five brick prisms in stretcher bond, prism with h/t ratio of 5.44 is tested.

The ultimate stress and MOE of MKBP of various h/t ratios are presented in Table 3. The efficiency of the MKBP of h/t ratio 5.44 and 2.57 are 0.32 and 0.27 respectively. Both these prisms are 5 brick in height, but the type of bonding used in construction are stretcher bond and English bond. Five brick height stretcher bonded MKBP tested in this investigation is more efficient than 5 brick height English bonded MKBP tested. In stretcher bond, bricks are subjected to biaxial compression only as against tri-axial compression in English bond, increasing the compressive strength of masonry. The efficiency of MKBP with h/t ratio of 3.1 and 4.15 are 0.32 and 0.36 respectively. As h/t ratio increases the masonry becomes stiffer and hence the Modulus of Elasticity increases.

Using Regression analysis[13], an analytical expression of $E_m = C\ f'_m$ where C varies from 250 to 1100 was proposed relating the modulus of elasticity of masonry and the strength of the masonry. Value of C calculated in this investigation is between 507 and 912 and it is well within the range of 250–1100. Compression test on burnt clay brick prisms[20] were conducted and equations were put forth to find the compressive strength of the masonry, in terms of the compressive strength of the brick and mortar.

The compressive strength of MKBP investigated in this study for various h/t ratio is presented in Table 3 and it is well compared with the compressive strength of masonry evaluated using the relationship suggested by Gumaste *et al.*[20] The variation in the strength of the masonry is due to the variation in compressive strength of the masonry unit and the modular ratio of masonry unit and mortar. The failure pattern of MKBP with h/t ratio of 3.1 and 2.57 are shown in Fig. 2. The prisms initially crack vertically at the centre and not at the joints. As the stress in the masonry approaches the ultimate, the MKBP shows a crushing failure. This is because the compressive strength and MOE of MKGB is less compared to the compressive strength and MOE of cement mortar.

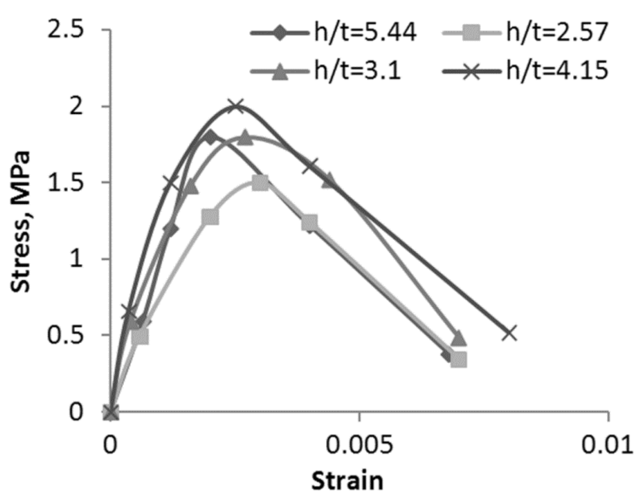

Fig. 1 — Stress-Strain curve for MKBP

Fig. 2 — Failure patterns of MKBP

The cost of the raw materials required for laboratory production of one number of MKGB used in this study is given below.

Cost for 1 Metakaolin geopolymer brick
Metakaolin - 0.2 Kg @Rs.35/Kg=Rs.7
Flyash - 0.2 Kg
Sand - 2.4 Kg @ Rs.1.25/Kg=Rs.3
AAS - 0.4Kg@Rs.12.5=Rs.5
Total - Rs.15.

Conclusions

This research has been performed with the general aim of synthesising FA-MK geopolymer bricks and to study the physical and mechanical properties of individual brick and the FA-MK geopolymer brick masonry prisms. The MKGB has 3–5% water absorption, µ as 0.2 and 2340 MPa as MOE. MKGB performs well with cement mortar in MKGB masonry. Production cost of Metakaolin can be brought down by the increased demand and state of the art technology in calcination. Use of extensometer in the place of LVDT can result in accurate strain measurement. The ultimate stress increases with h/t ratio, the ultimate strain is around 0.007 for the prisms except for MKBP with h/t ratio of 4.15, where the ultimate strain increases to 0.008. MKGB can be used in masonry construction with cement mortar. MKBP has not failed in bonding and has failed only by vertical splitting and then by crushing ensuring perfect bond with the mortar.

References

1 Davidovits J, *Geopolymer Chemistry and Applications*, 4th edn, Institut Géopolymère, Saint-Quentin, France, 2015, 1–16.
2 Rahier H Simons W, van Mele B & Biesemans M, Recent literature in geopolymer science and technology, *J Mater Sci*, **32** (2010) 2237–2247.
3 Kong L Y, Sanjayan G & Kwesi S, Comparative performance of geopolymers made with metakaolin and fly ash after exposure to elevated temperatures, *Cem Concr Res*, **37** (2007) 1583–1589.
4 Hawa A, Prachasaree W & Tonnayopas D, Effect of water to powder ratios on the compressive strength and microstructure of metakaolin based geopolymers, *Indian J Eng Mater Sci*, **24** (2017) 499–506.
5 *Indian Standard Specification for Fly Ash for use as Pozzolona and Admixture*: *IS 3812*, Bureau of Indian Standards, New Delhi, India, 1981.
6 *Indian Standard Code for Specification of Calcined Clay Pozzolona*: *IS 1344*, Bureau of Indian Standards, New Delhi, India, 1981.
7 Kalaiyarrasi A R R, & Partheeban P, Influence of Si/Al ratio on the compressive strength of metakaolin based geopolymers, *Int J Earth Sci Eng*, **9** (2016) 87–91.
8 *Indian Standard Code of Specification for Sand for Masonry Mortars*: *IS 2116*, Bureau of Indian Standards, New Delhi, India, 1980.
9 *Indian Standard Code for Sodium Silicate Specification: IS 381*, Bureau of Indian Standards, New Delhi, India, 1995.
10 *Indian Standard Code of Practice for Structural Use of Unreinforced Masonry IS 1905*, Bureau of Indian Standards, New Delhi, India, 1987.
11 *Indian Standard Code of Practice for Preparation and Use of Masonry Mortars IS 2250*, Bureau of Indian Standards, New Delhi, India, 1981.
12 *Indian Standard Code of Methods of Tests of Burnt Clay Building Bricks: IS 3495 (Parts 1 to 4)*, Bureau of Indian Standards, New Delhi, India, 1992.
13 *Indian Standard Code for Non-destructive Testing of Concrete-Methods of Test: IS 13311 (part I)*, Bureau of Indian Standards, New Delhi, India, 1992.
14 Hemant B Kaushik, Durgesh C Rai & Sudhir K Jain, Uniaxial compressive stress–strain model for clay brick masonry, *J Mater Civil Eng*, **19** (2007) 728–739.
15 ACI 530.1-02/ASCE 6-02/TMS 602-02 *Specification for Masonry Structures*, *Reported by the Masonry Standards Joint Committee* (MSJC), ASTM International, 100 Barr Harbor Drive, P.O. box C-700 West Conshohocken, Pennsylvania 19428-2959, United States.
16 Brencich A, Corradi C, Gambarotta L, Mantegazza G & Sterpi E, *Compressive Strength of Solid Clay Brick Masonry under Eccentric Loading*, Research work by the Department of Structural and Geotechnical Engineering, University of Genoa, Italy, 2002.
17 *IS 12894 Pulverized Fuel Ash-Lime Bricks* - [CED 4: Building Limes and Gypsum Products], 2002.
18 Venugopal K, Radhakrishna J, & Dar M A, Properties and Application of Geopolymer Masonry Units, *SSRG-Int J Civil Eng*, (2015) 117–119.
19 Khater H M, Ezzat M, & Abdeen El Nagar M, Alkali Activated Eco-friendly Metakaolin/Slag Geopolymer Building Bricks, *Chem Mater Res*, **8** (2016) 21–32.
20 Gumaste K S, Nanjunda Rao K S, & Venkatarama Reddy B V, Strength and Elasticity of Brick Masonry prisms and Wallette's under compression, *Mater Struct*, **40** (2007) 241–253.